Measurements of Heat & Combustion Products in Reduced-Scale Compartment Fires

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NIST/BFRL Fire Research Division

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Acknowledgements

Dedication:

To Jack Lee who recently passed away and who provided indispensable support for this and many other projects

Collaborators:

NIST Fire Research - Kevin McGrattan, Bill Pitts

Hughes Associates - Jason Floyd

Project Background/Motivation

- Field models for fires require complete and accurate data for chemistry submodel development to improve predictions of underventilated fire conditions including the radiative environment, burning rate, toxic gas production, etc.

- An experimental database of fire measurements is needed that provides opportunities for model validation and characterizes flashed-over enclosure fire dynamics for different fuel types, fuel distributions, ventilation conditions, etc.

Experimental Conditions

Completed in reduced-scale (2/5) enclosure:

- 17 experiments, 56 quasi-steady fire conditions
- natural gas, heptane, toluene, methanol, ethanol, polystyrene
- ½-width and full-width doorways (heptane & natural gas)
- Spray and pool burning comparison (heptane)
- Enclosure lining comparison (natural gas & heptane)

305 kW
Methanol

328 kW
Ethanol

370 kW
Heptanes

200 kW
Toluene

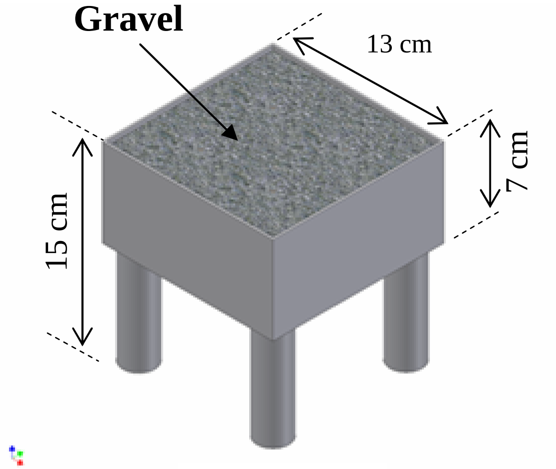
340 kW
Polystyrene

Experimental Measurements

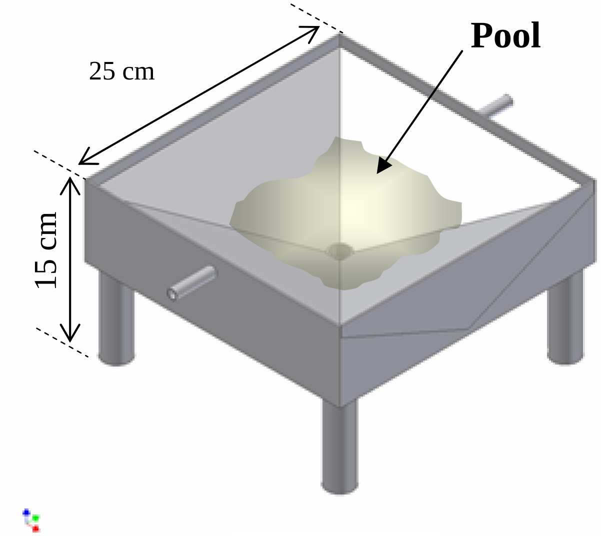
Generated measurement database including:

- O_2, CO_2, CO, THC, soot and temperature in the upper layer and exhaust stack, heat release rate
- Composition of hydrocarbons (up to C_6) in upper layer using GC
- Surface heat fluxes and temperatures
- Doorway temperatures and pressures

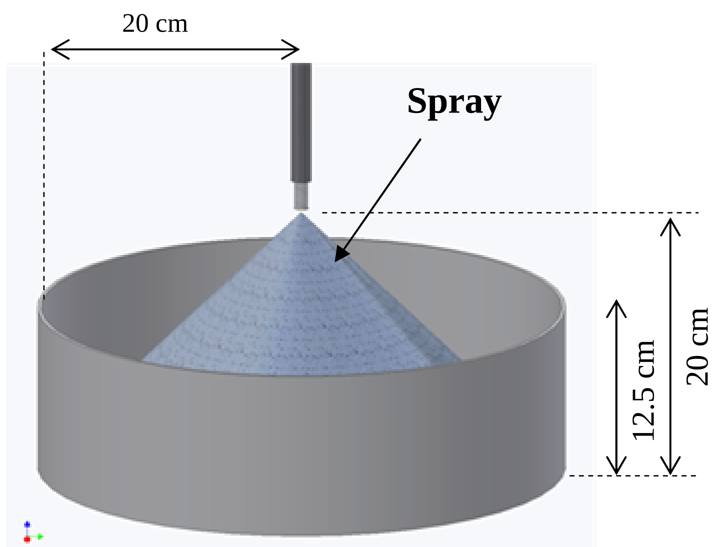
Burner Designs



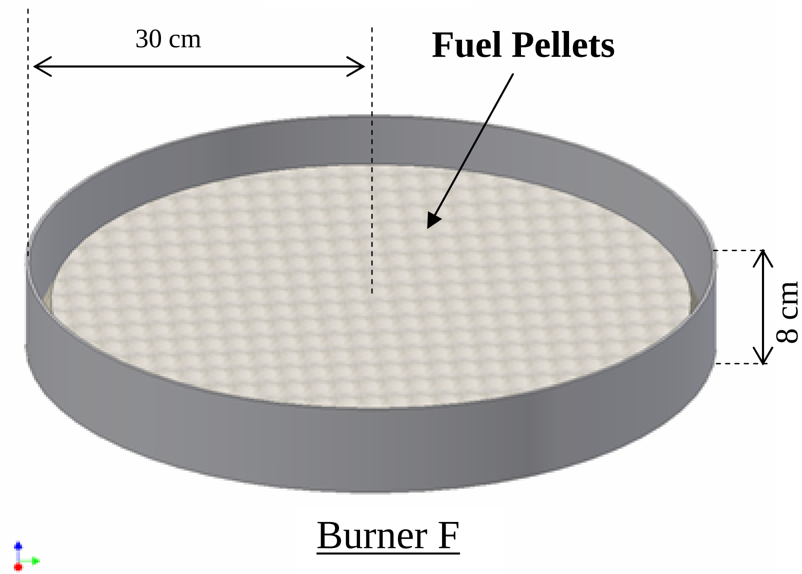
Burner A



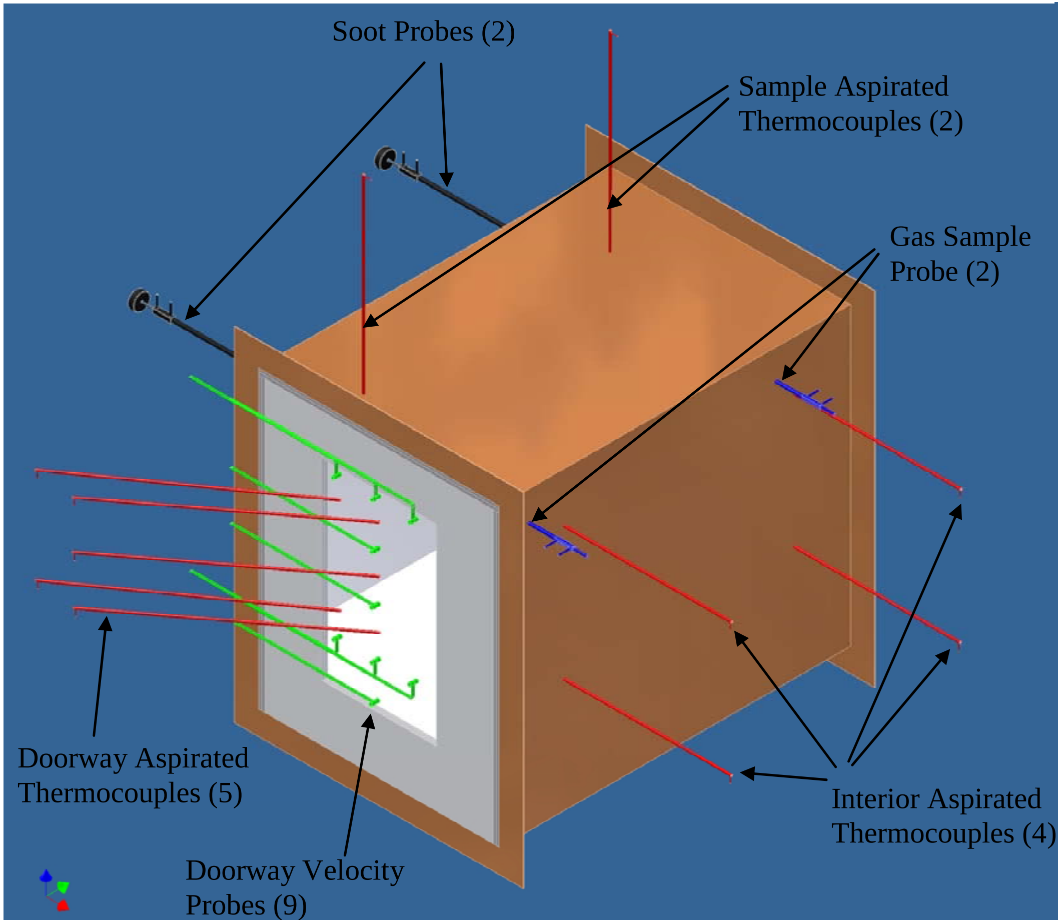
Burner B

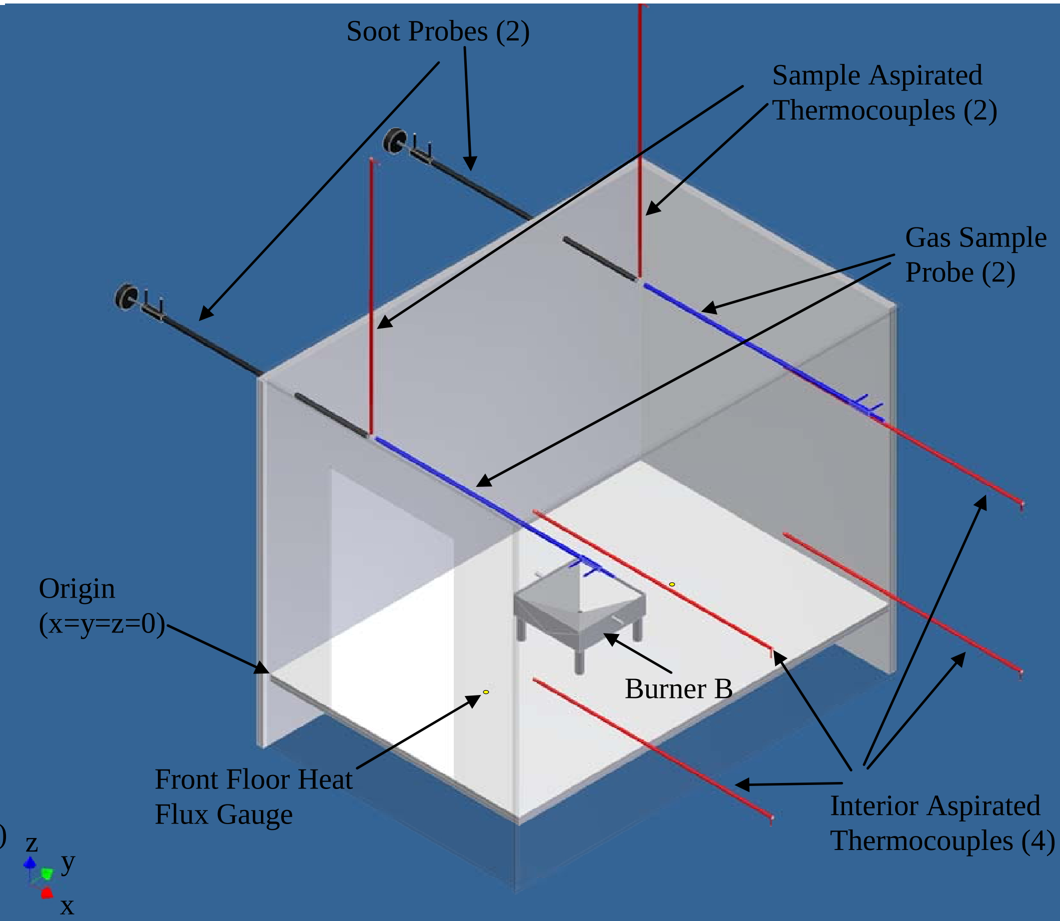


Burner C

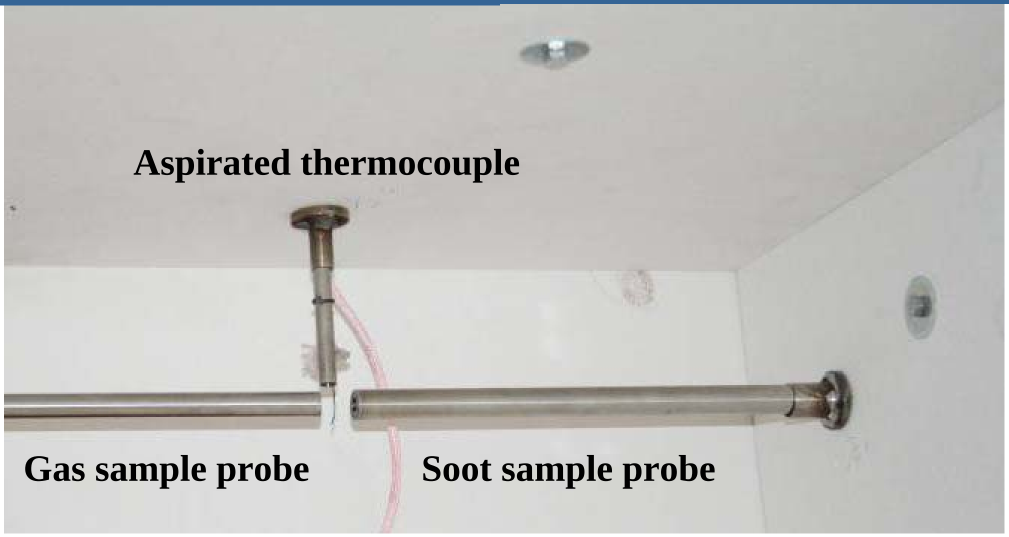


Burner F



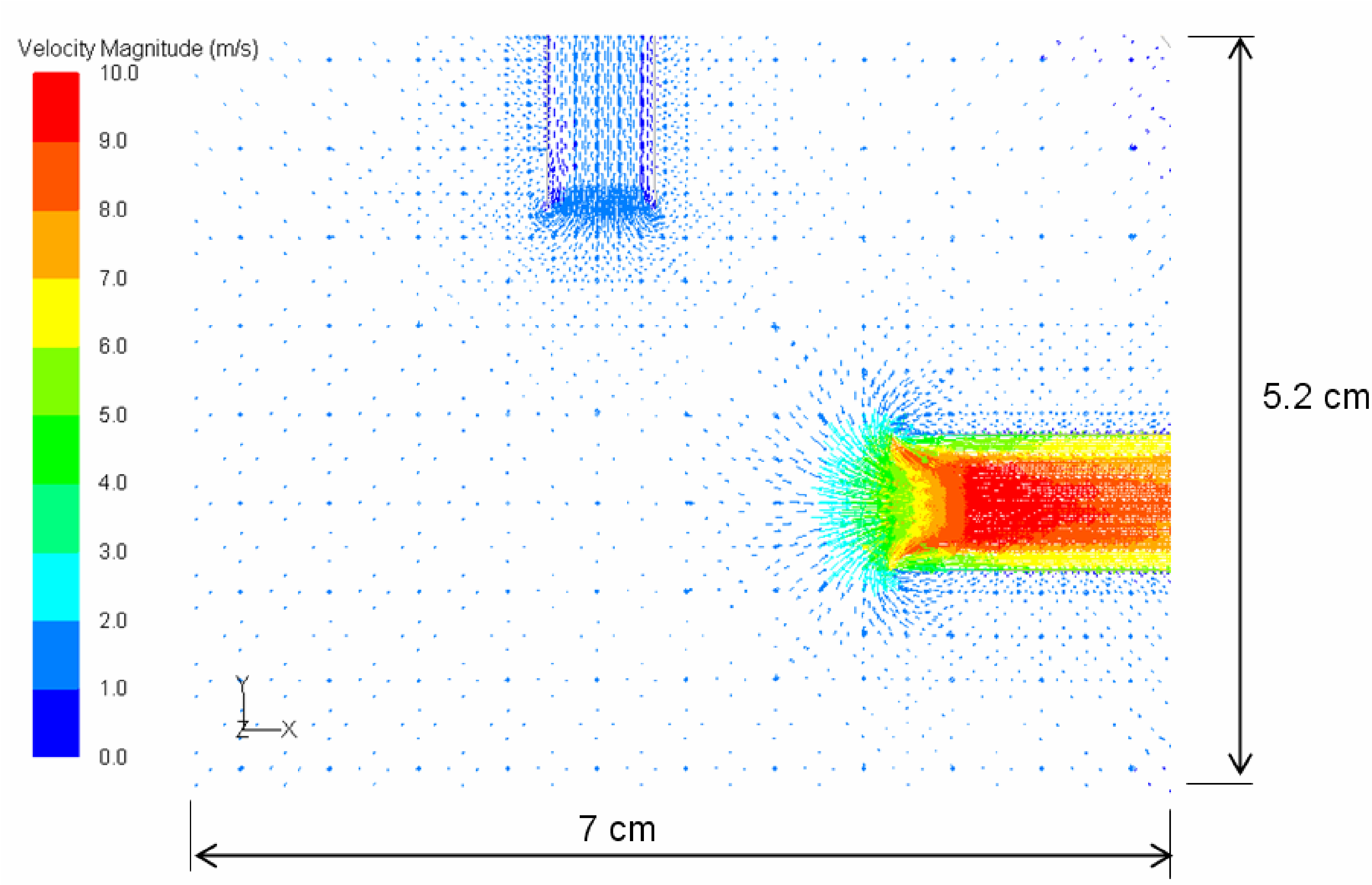


Aspirated TCs
Bi-directional Probes
Extractive Soot Probes
Cooled Sample Probes
Heat Flux Gauges

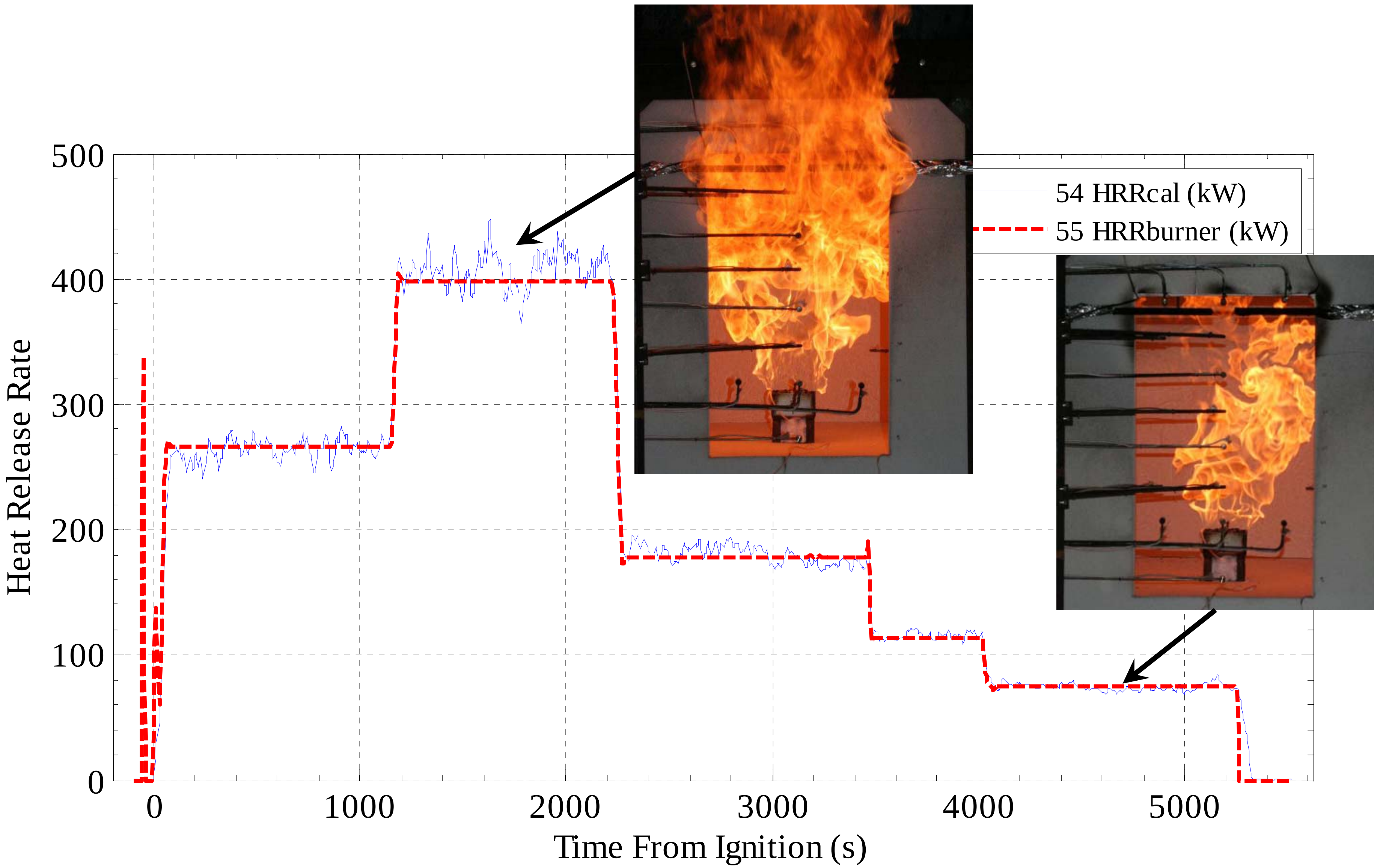


Instrumentation

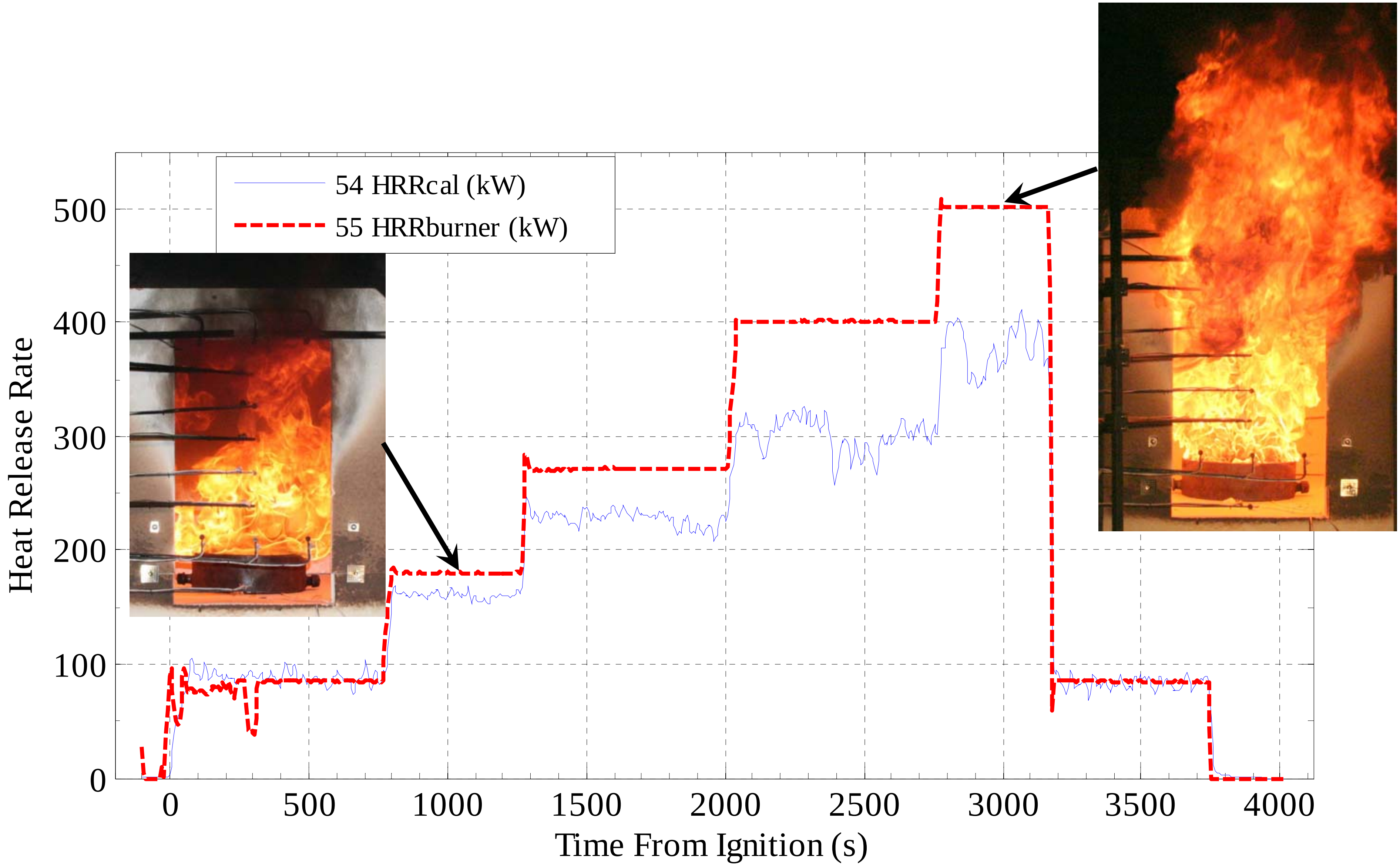
Velocity field across cross-section of the probes position



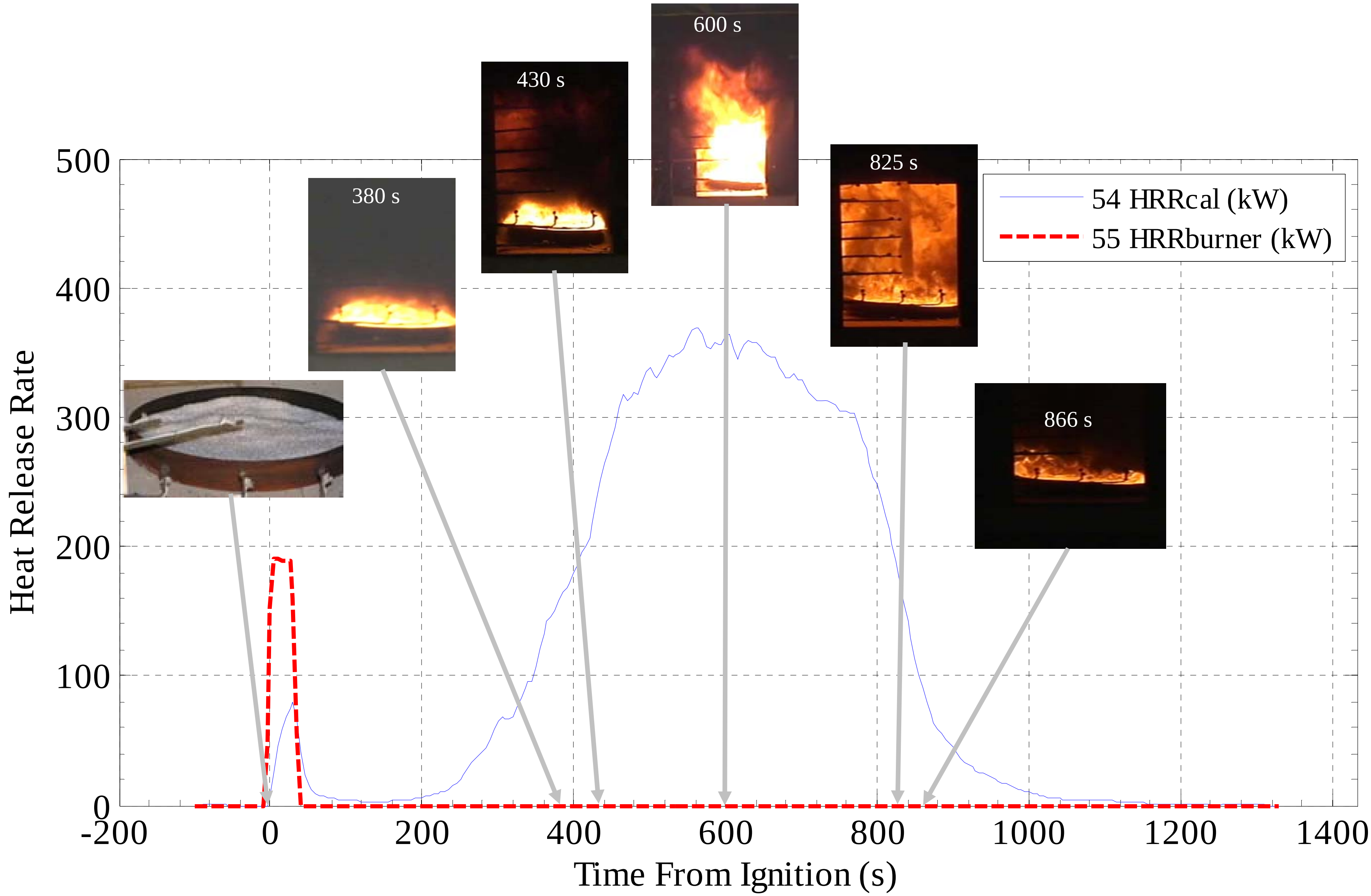
Heat release rate for natural gas test using Burner A



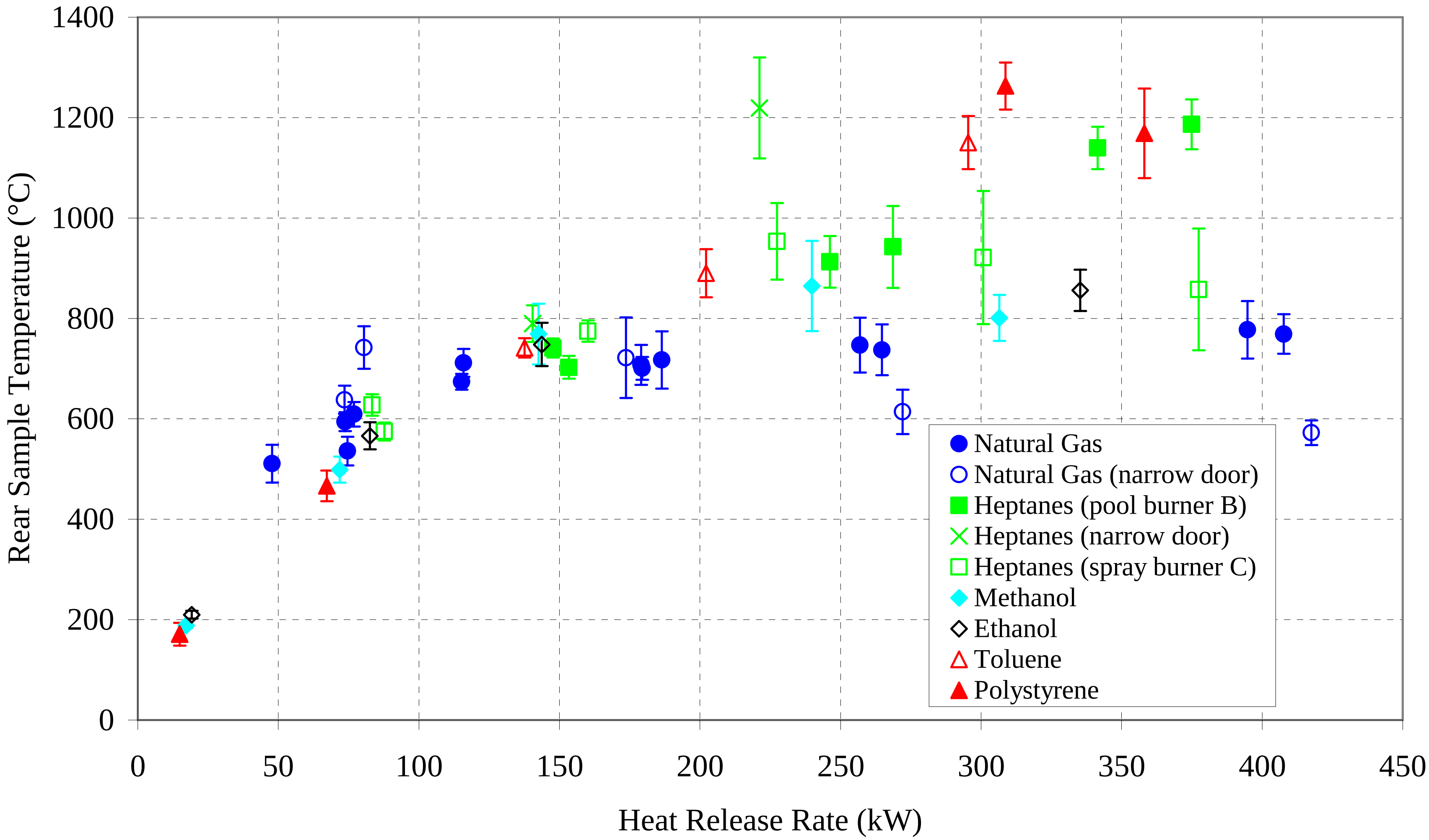
Heat release rate for heptane test (spray burner)



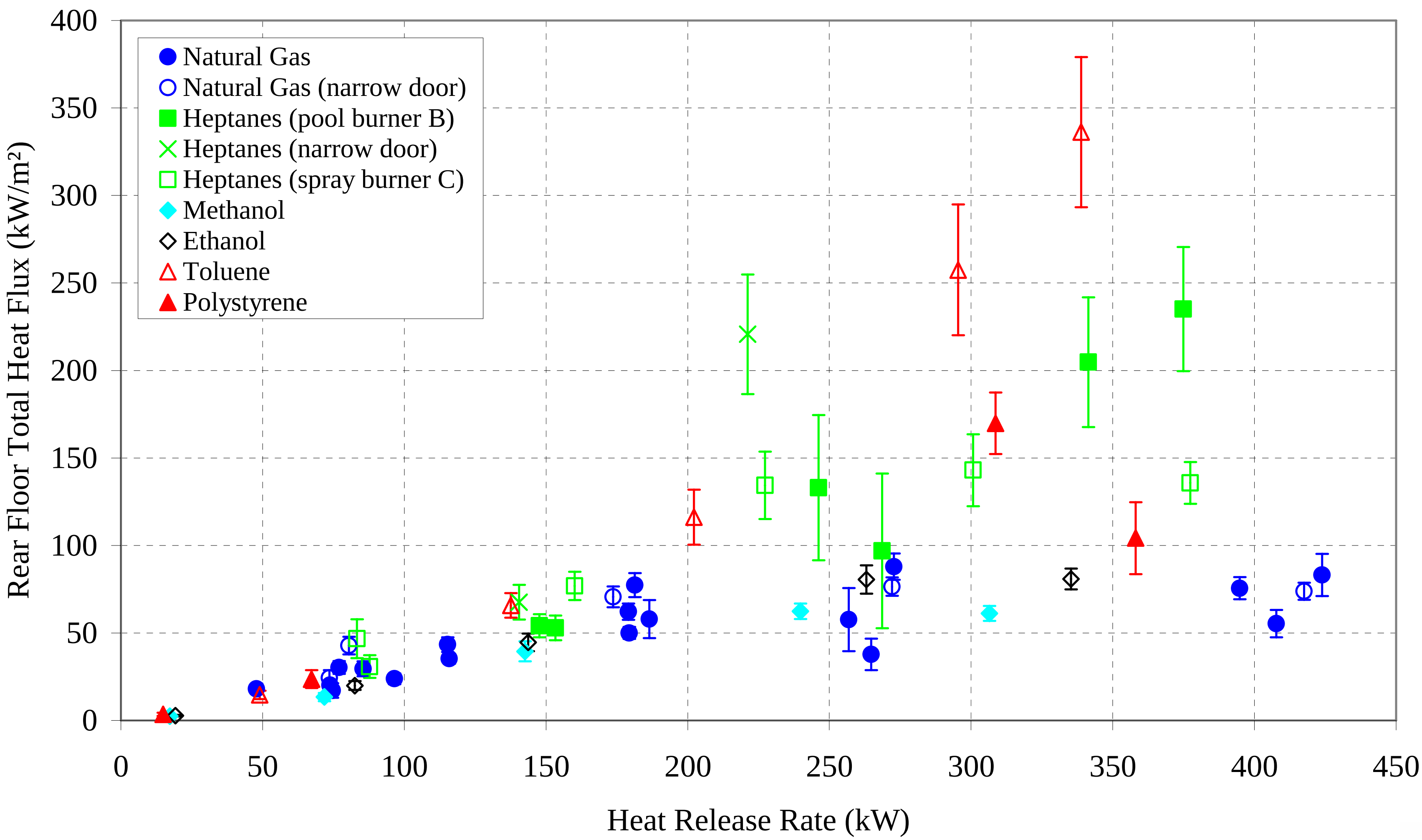
Heat release rate for polystyrene test.
A heptane spray fire ignited 6 kg of polystyrene pellets



Steady state average temperatures from aspirated thermocouple measurement at rear gas sampling location



Steady state total heat flux at rear floor location.



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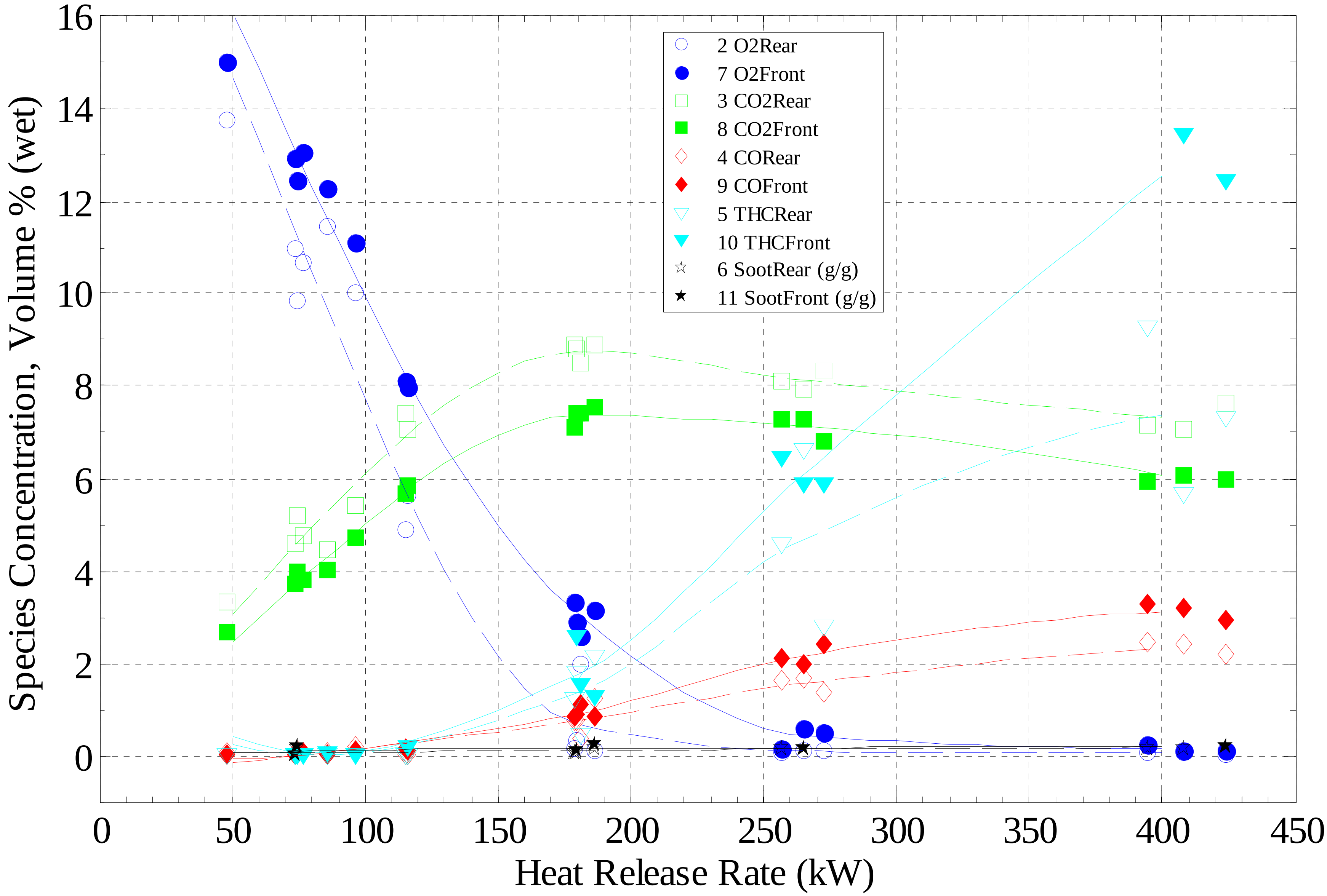
Steady state average gas species and soot for natural gas full doorway tests. Lines are piecewise cubic polynomial fits.



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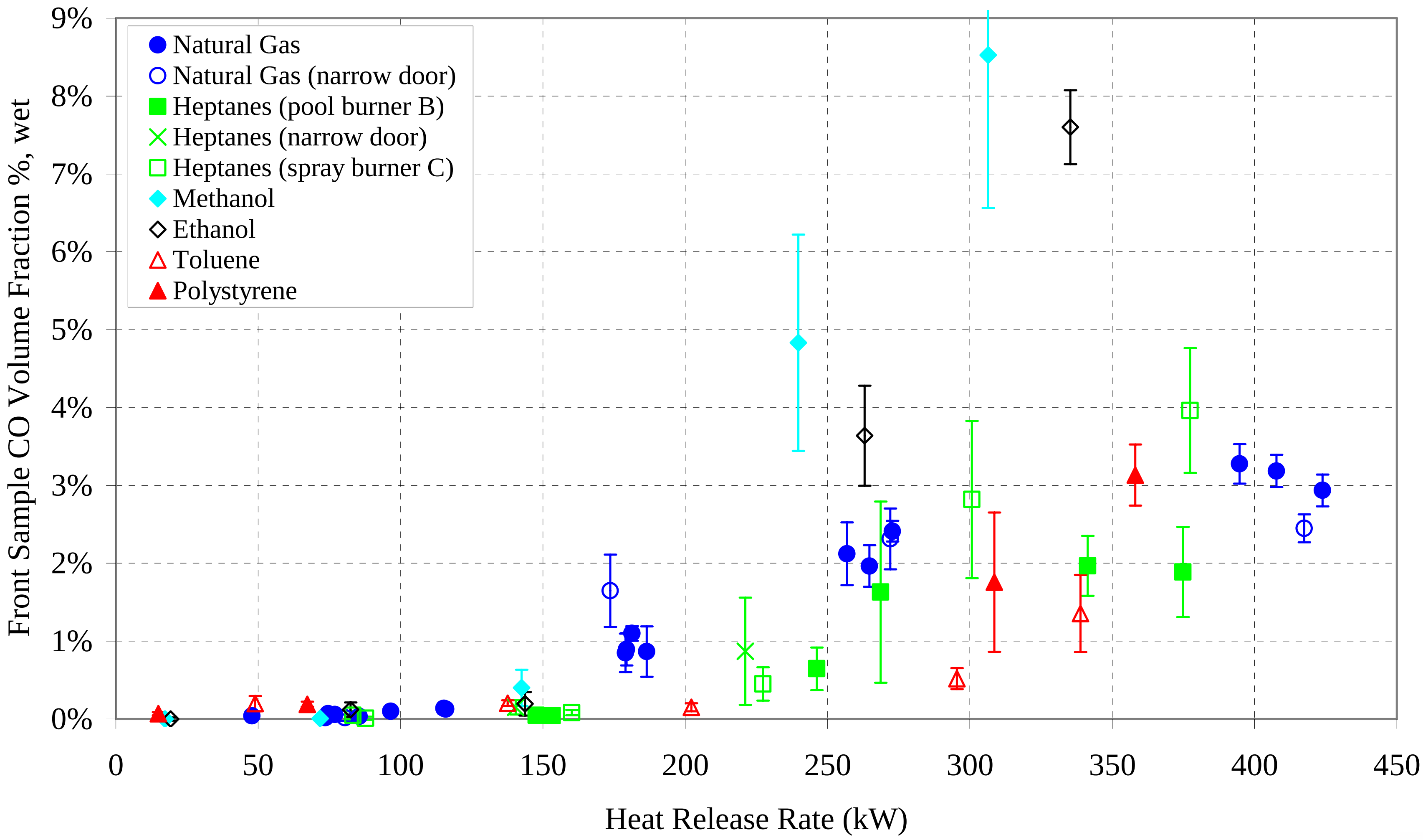
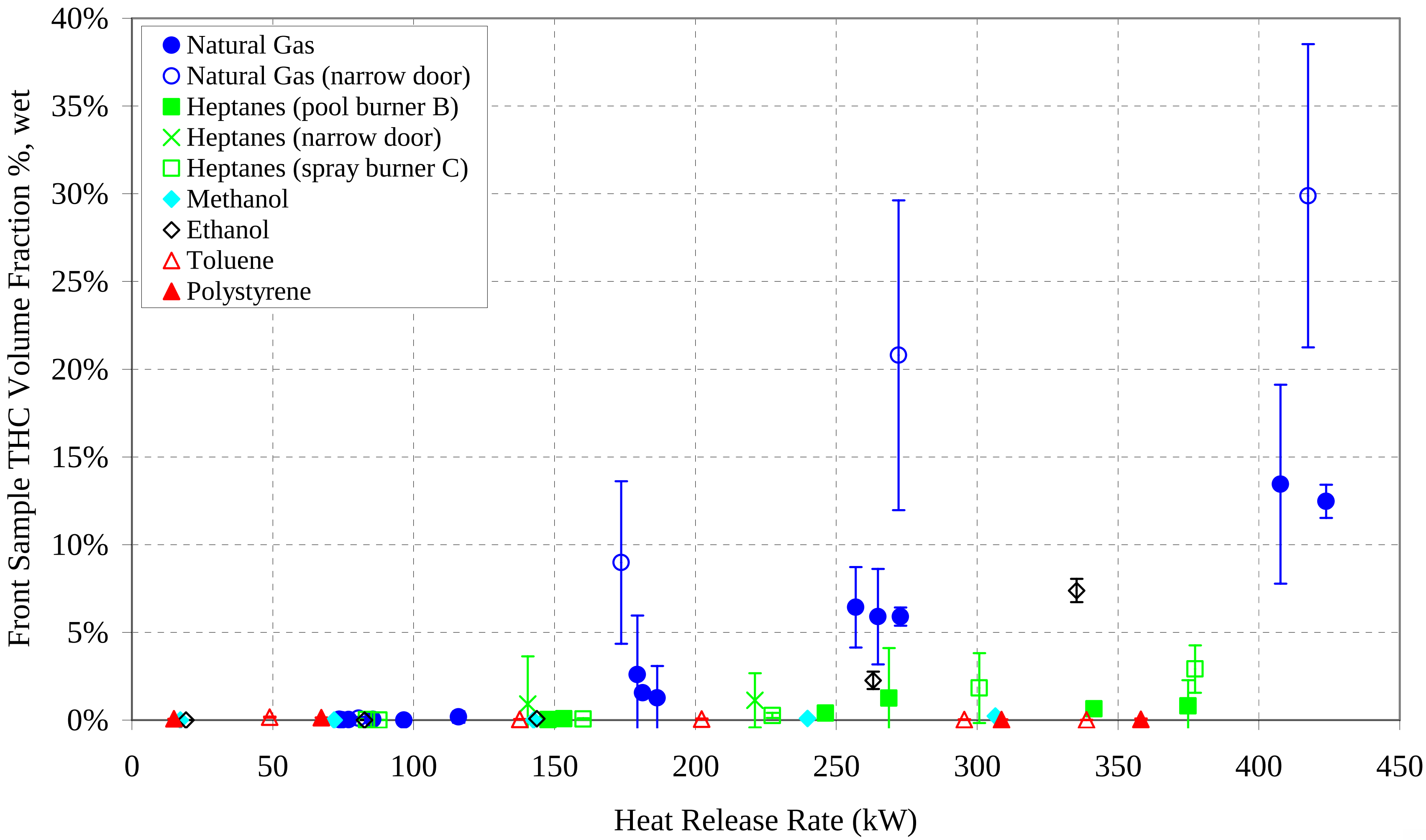
Steady state average carbon monoxide volume fraction at front sample probe location



Steady state average total hydrocarbon volume fraction at front sample probe location



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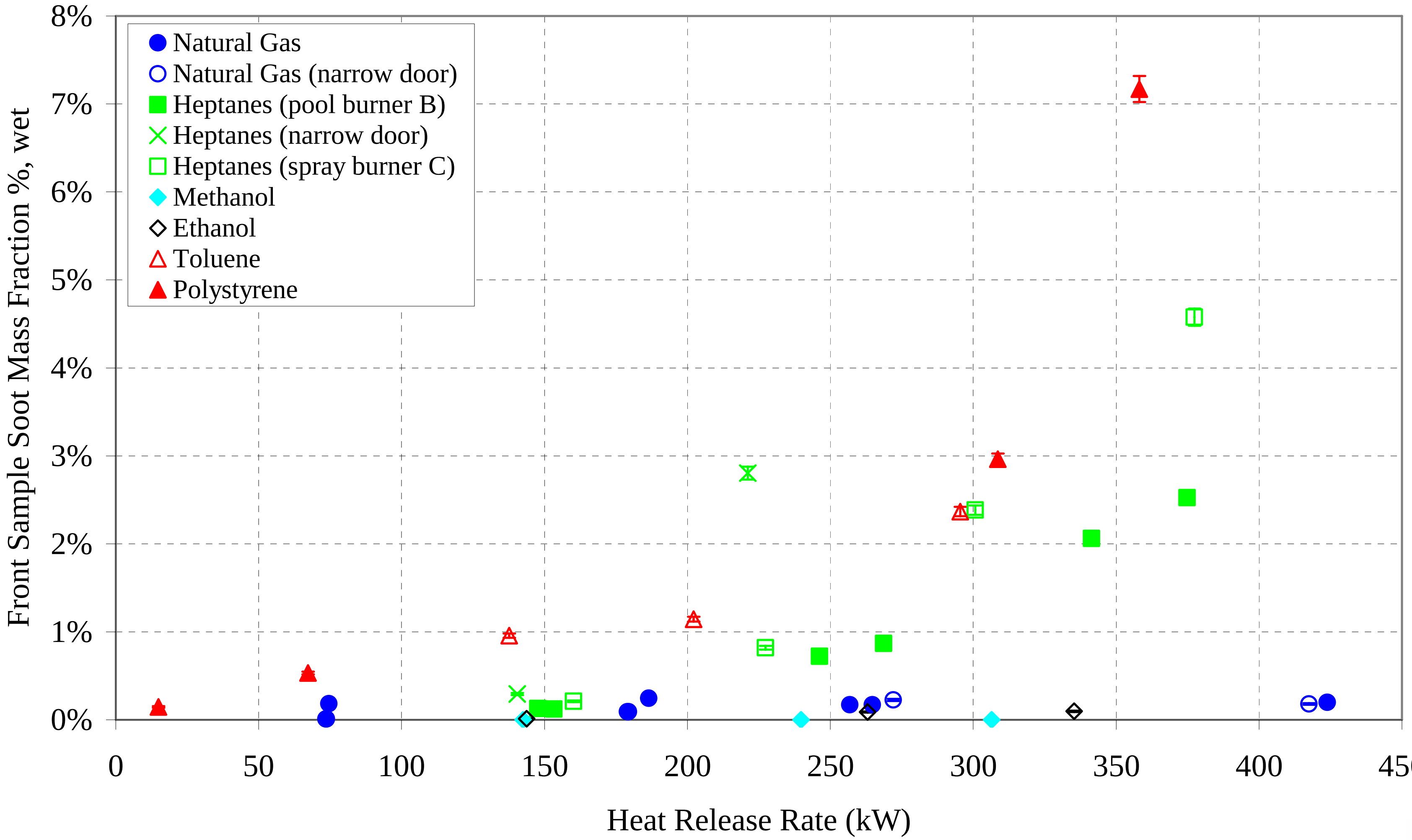
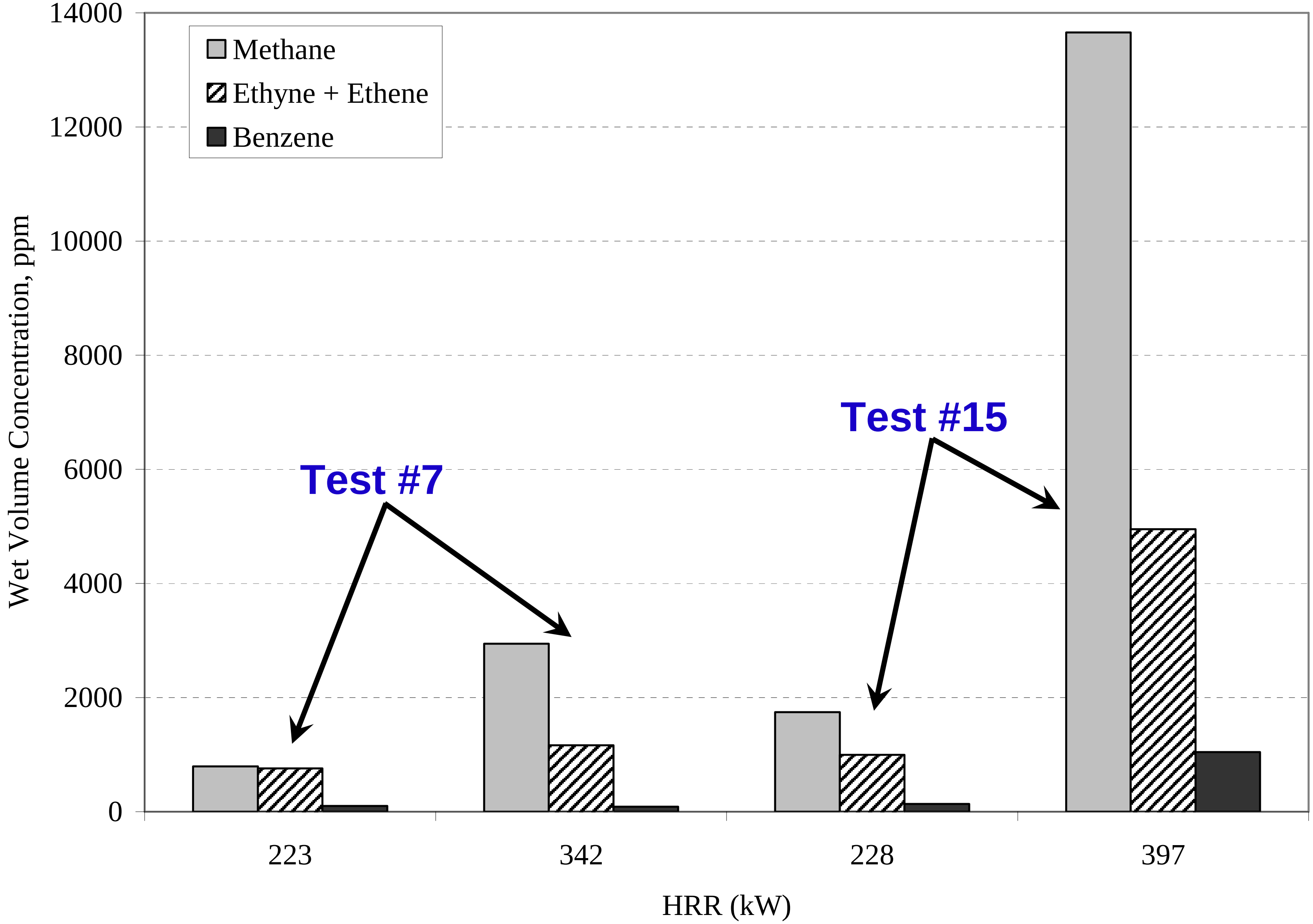
Steady state gravimetric soot mass fraction at front sample probe location



GC measurements of methane, ethyne plus ethene, and benzene for two heptane fires at front gas sample probe



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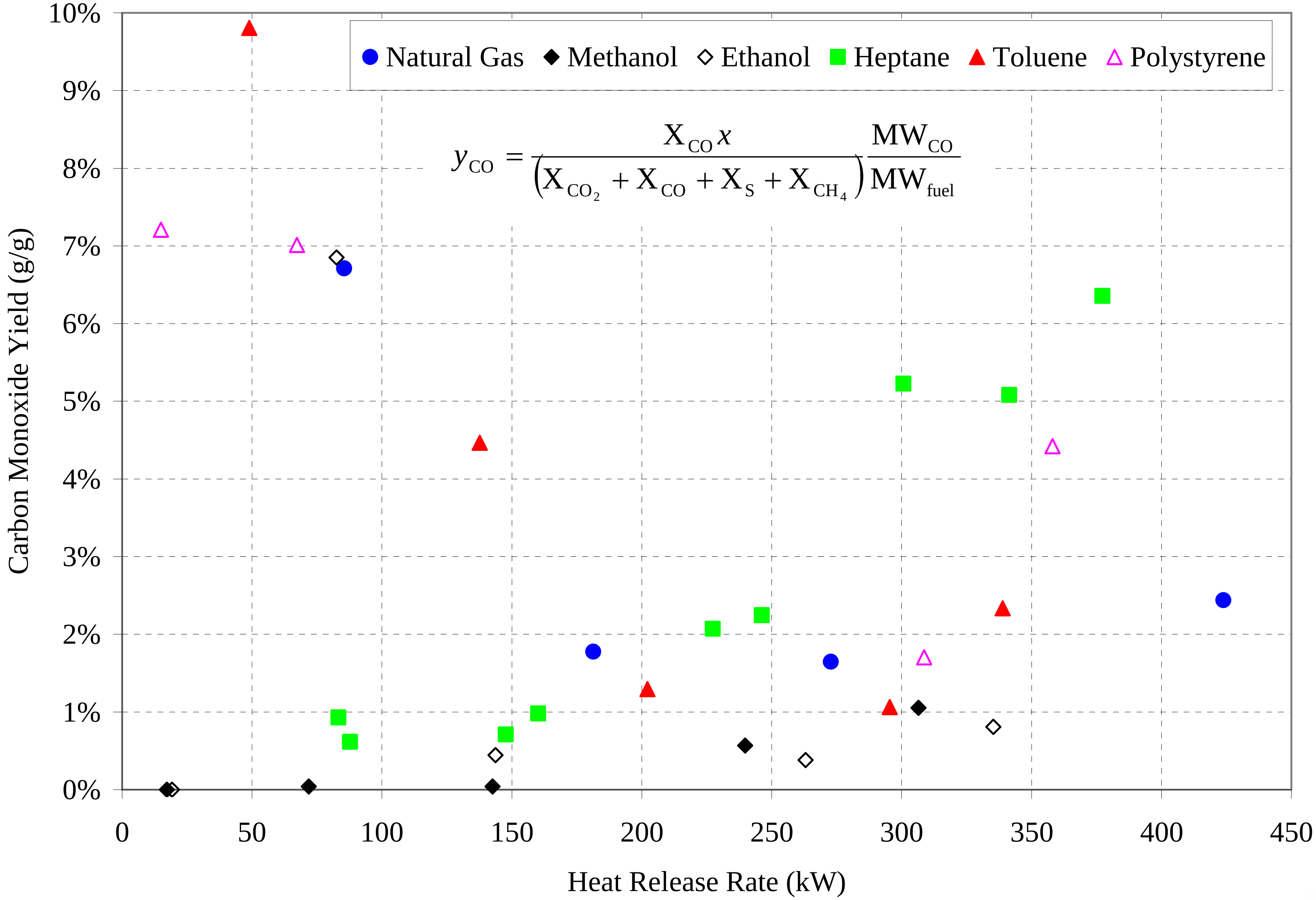
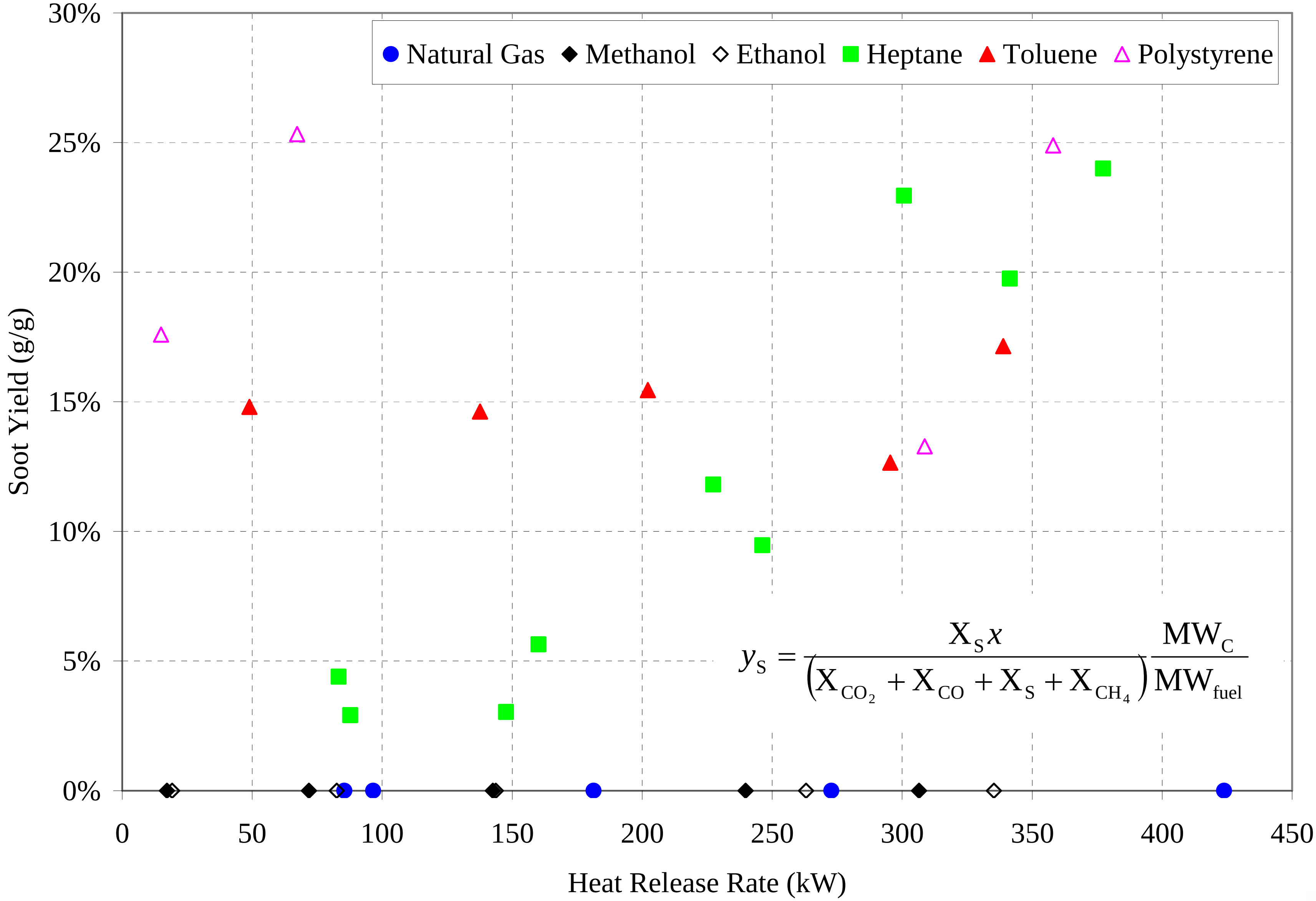
Exhaust stack CO yield as a function of heat release rate during the steady burning periods for each fuel



Exhaust stack soot yield as a function of heat release rate during the steady burning periods for each fuel



$$y_S = \frac{X_S x}{\left(X_{CO_2} + X_{CO} + X_S + X_{CH_4}\right)} \frac{MW_C}{MW_{fuel}}$$

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Mass fraction vs. the mixture fraction calculated by the single-parameter mixture fraction model

Mixture fraction - a non-dimensional quantity representing the mass fraction of a species, at a particular location, that was originally part of the fuel stream

For mixture fraction based on carbon containing species:

$$Z = Y_F + Y_{co}\frac{MW_F}{x\,MW_{co}} + Y_{co_2}\frac{MW_F}{x\,MW_{co_2}} + Y_{Soot}\frac{MW_F}{x\,MW_{Soot}}$$

Where:

MW_i is the molecular weight of chemical species i

Y_i is the mass fraction of that species:

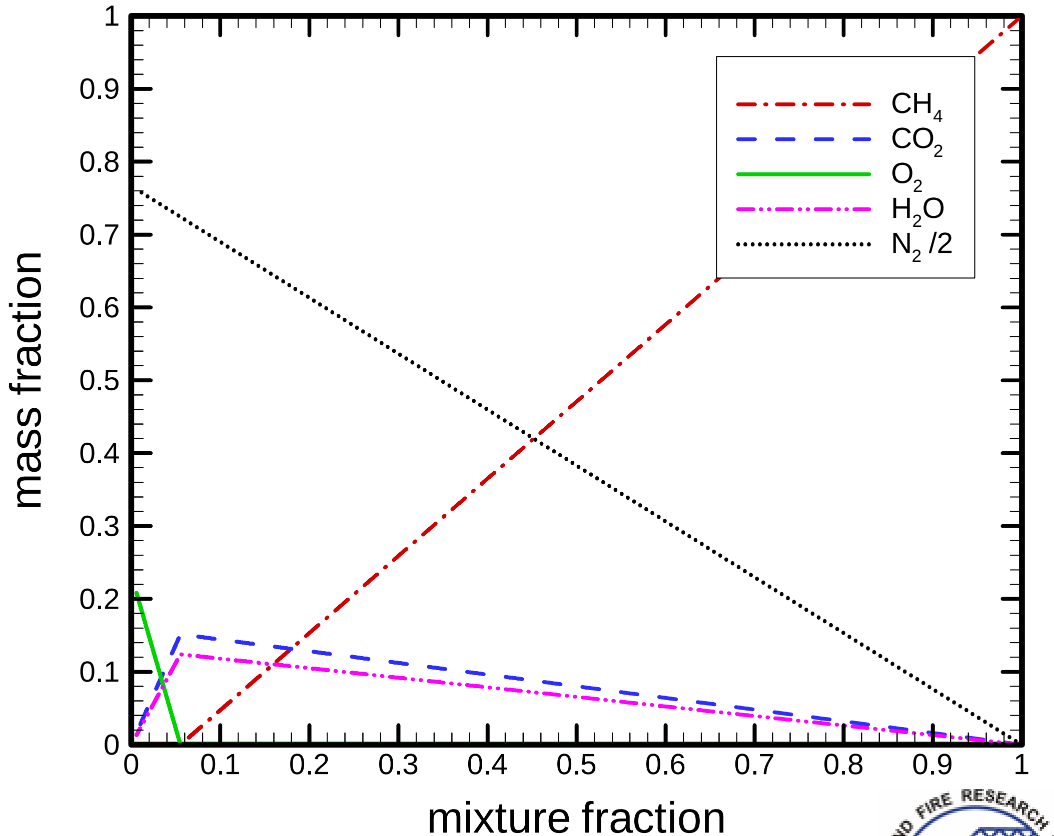
$$Y_i = X_i MW_i / MW_{tot}$$

$$MW_{tot} = \sum_i X_i MW_i$$

x is the number of carbon atoms in the parent fuel molecule $C_xH_yO_z$

MW_F is the molecular weight of the parent fuel

Also: $$\phi = \frac{(F/A)}{(F/A)_{st}} = \frac{Z}{(1-Z)(F/A)_{st}}$$



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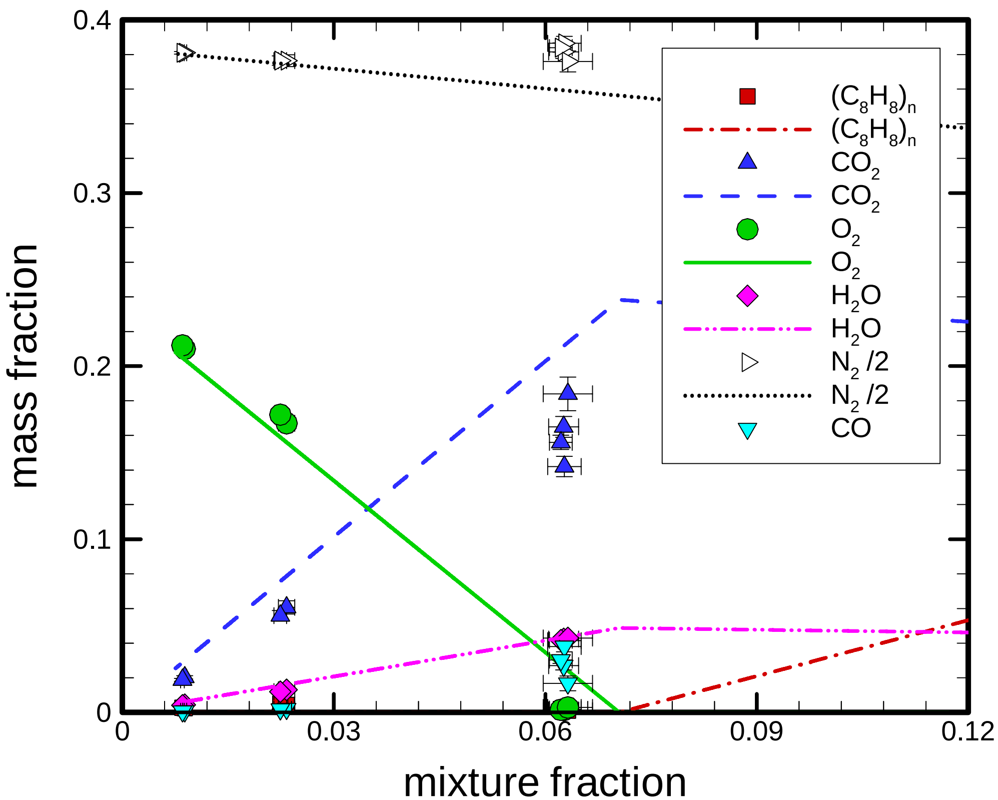
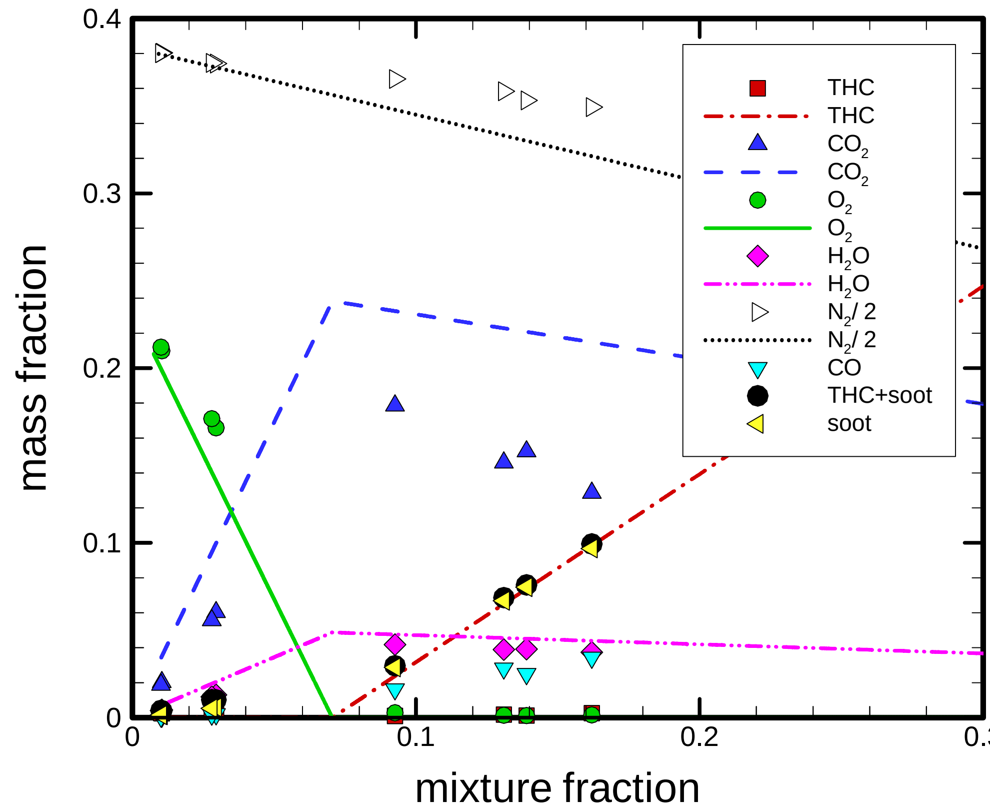
Mass fraction vs. the mixture fraction for time-averaged polystyrene fire measurements with and without soot

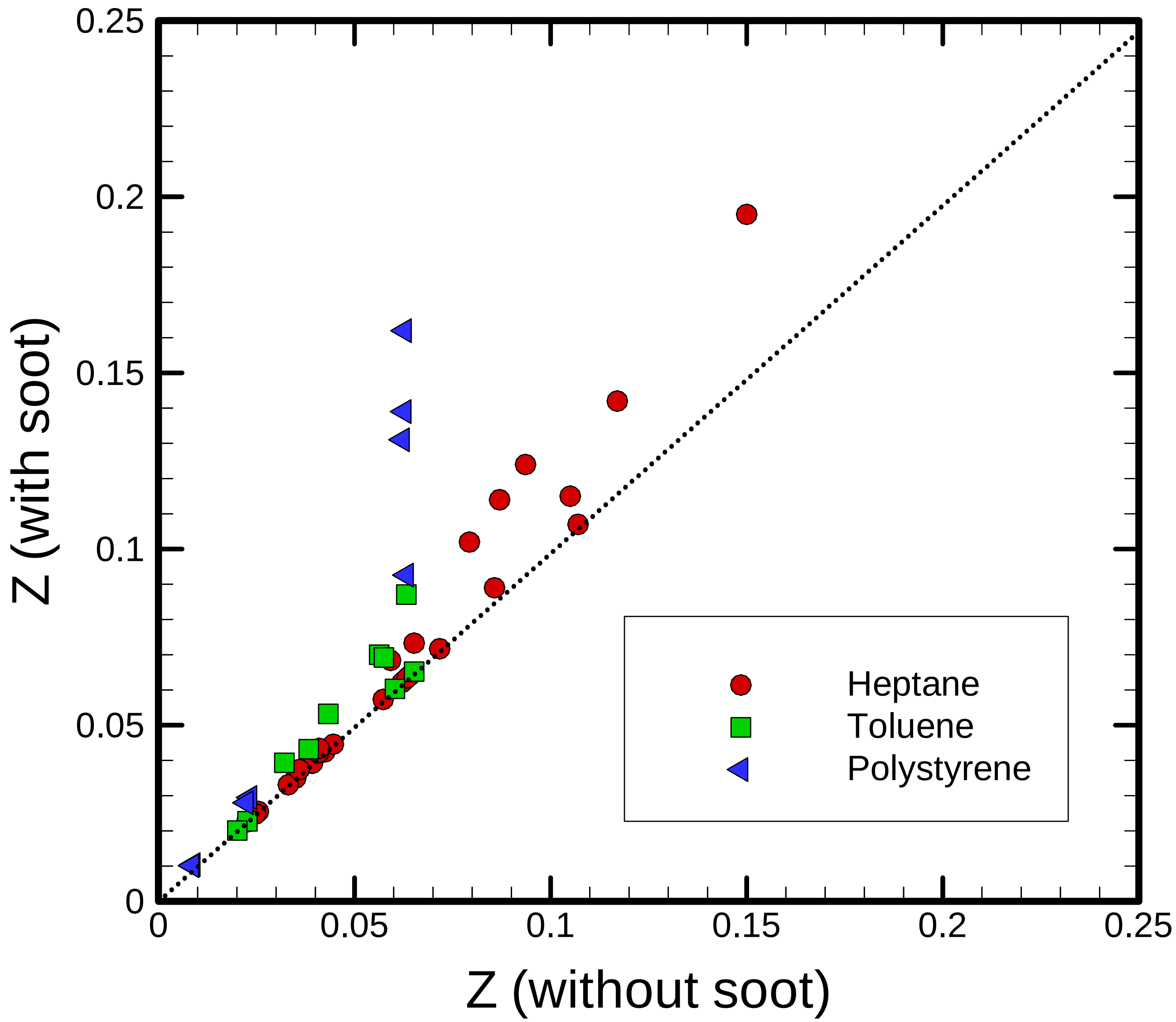


Without soot



With soot

Comparison of mixture fractions calculated with and without soot



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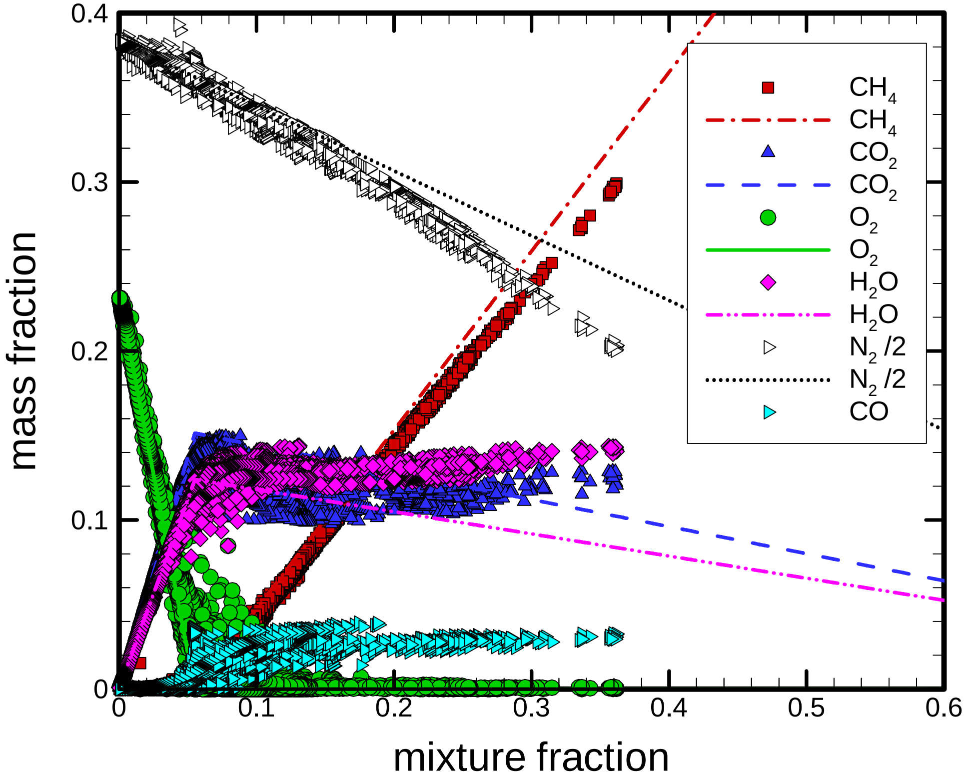
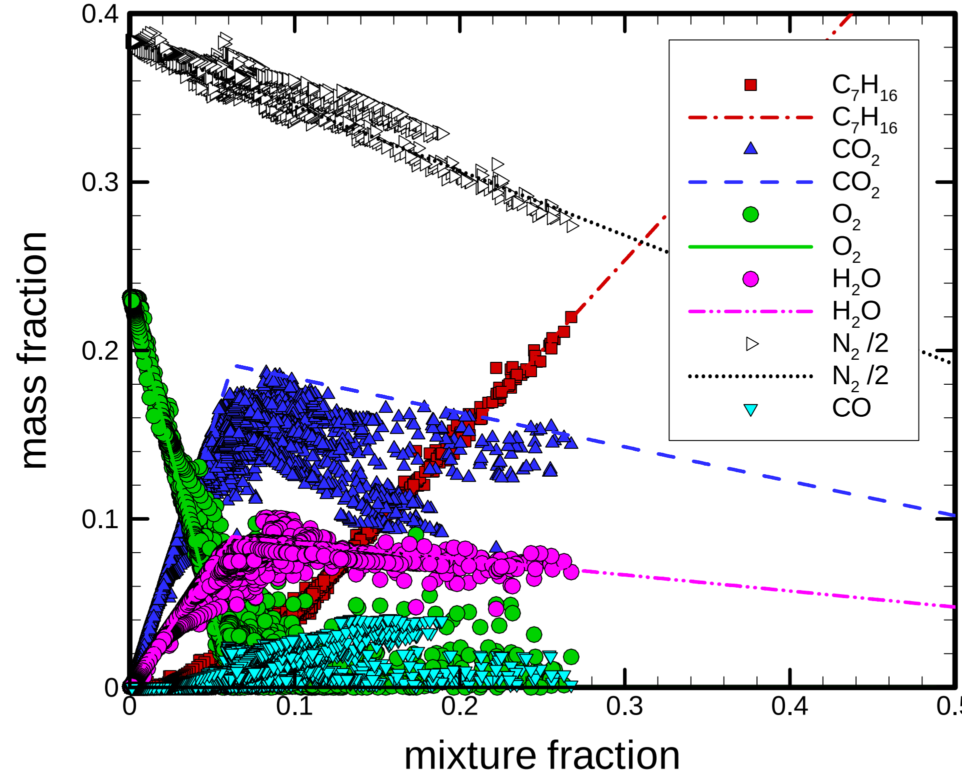
Mass fraction vs. the mixture fraction (without soot) for natural gas and heptane fire measurements

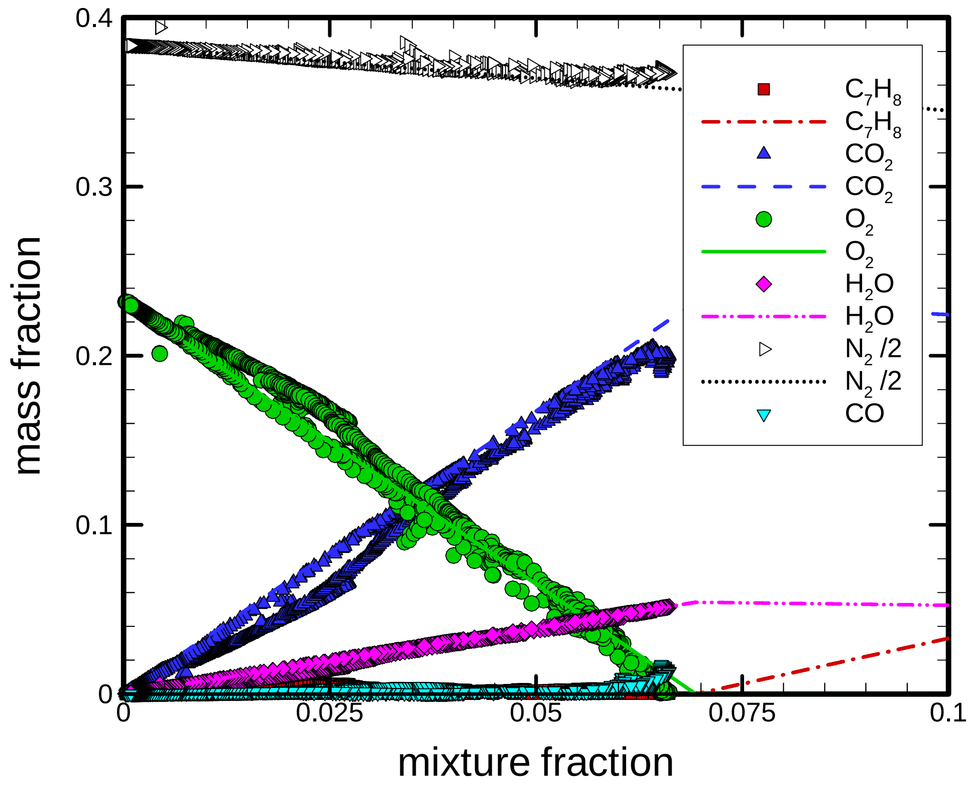


Natural Gas

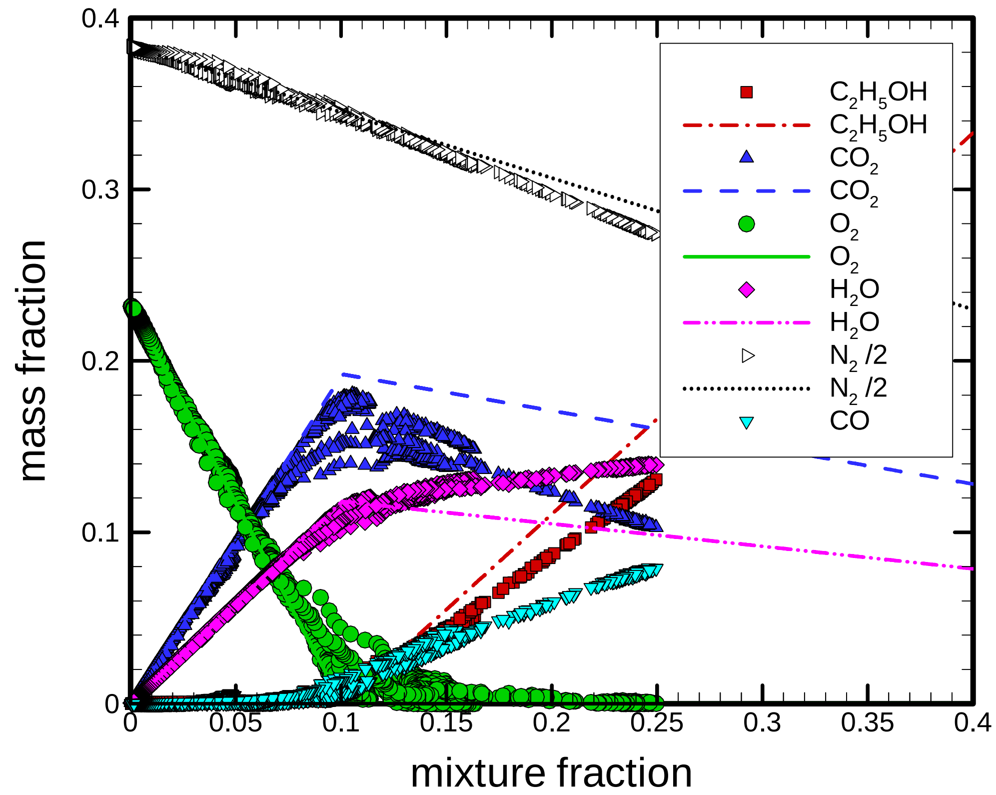


Heptane

Mass fraction vs. the mixture fraction (without soot) for toluene and ethanol fire measurements



Toluene



Ethanol

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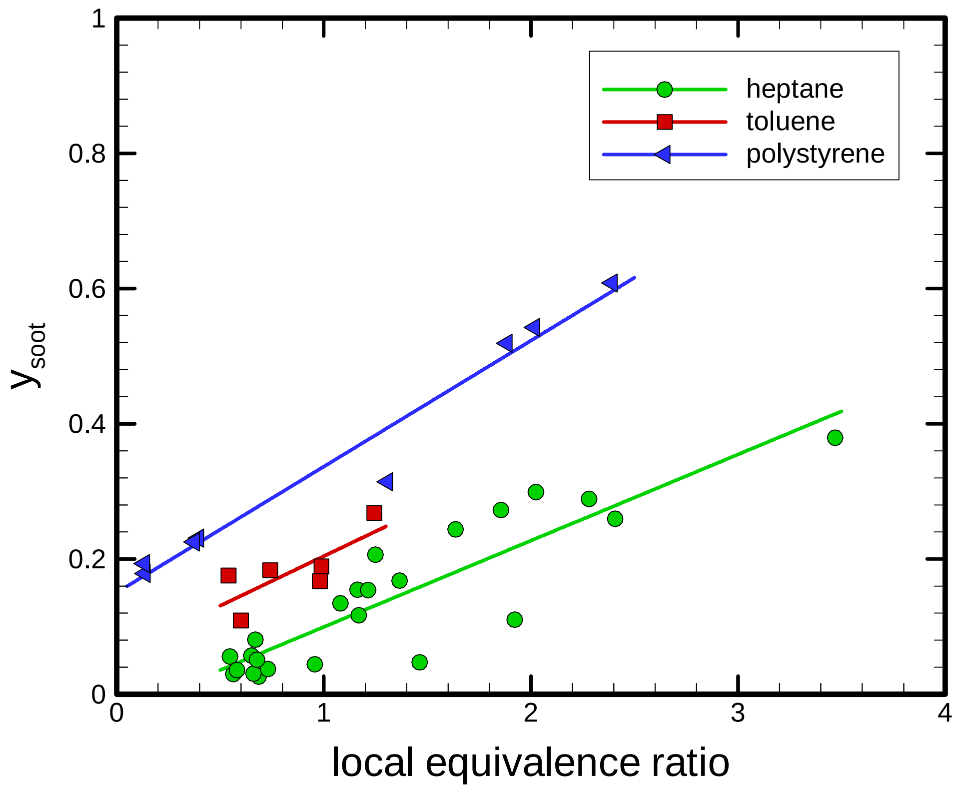
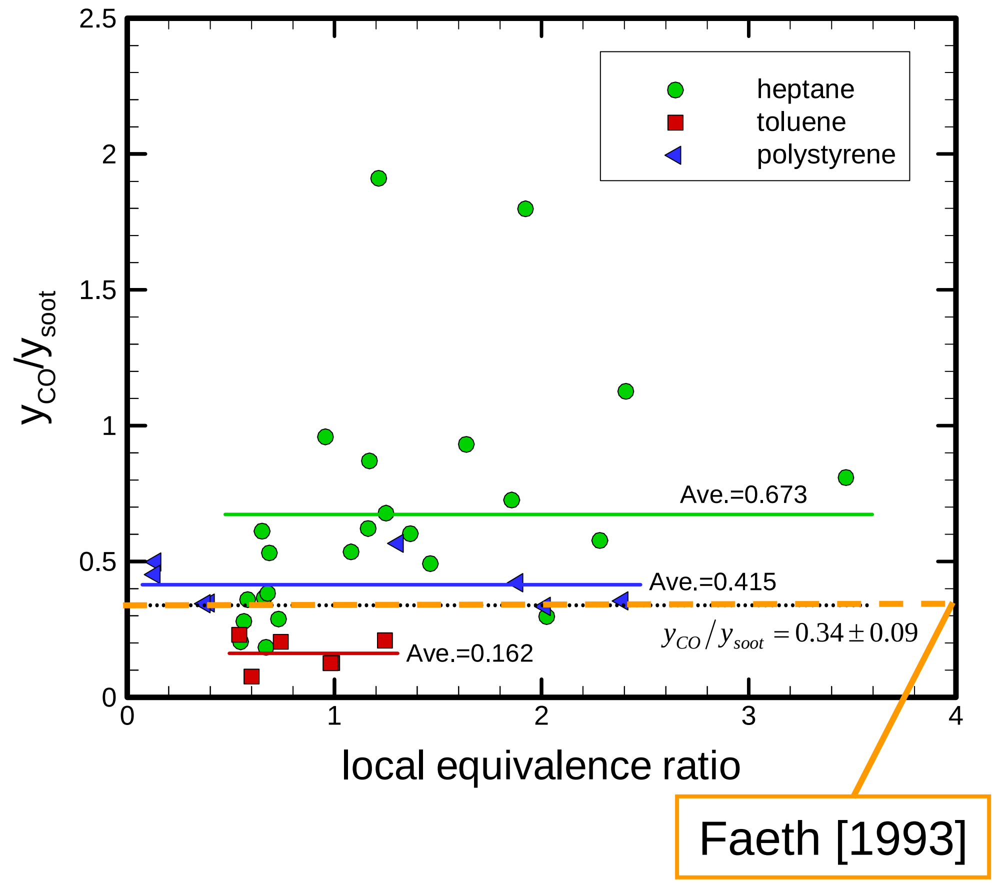
Soot yield and CO yield/soot yield ratio vs. the local equivalence ratio for heptane, toluene, and polystyrene fire measurements





- **Soot yield was a function of fuel type and local equivalence ratio in upper layer.**
- **Ratio of CO yield to soot yield was independent of local equivalence ratio.**

Conclusions

- Completed measurement sets including soot and hydrocarbons
- Evaluated burner designs, wall materials, & sample conditioning methods
- Identified major hydrocarbons and found methane as the predominant species in the upper layer for all fuels
- Found soot to be important in analyzing local mixture fraction results
- Confirmed that CO production is not well predicted by a simple state relation model
- Found interesting relationships between soot and CO yields for different fuels and equivalence ratios

Future Work

- Publish paper on RSE measurements (in review now)
- Make RSE measurement database available online
- Conduct ISO 9705 enclosure experiments this summer
  - Explore less ventilated enclosure conditions
  - Use and test performance of a different enclosure lining material
  - Implement improved gas sample conditioning
  - Implement improved thermocouple probe aspiration technique
  - Revisit fuels used in RSE series
  - Map species, temperature, & velocity in the doorway for heptane
  - Map species and temperature in the enclosure interior for heptane
- Develop experimental database for fire measurements associated with the ISO 9705 enclosure under flashed-over, underventilated conditions